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1. Introduction.

During the summer of 1959, Western Development Laboratories, a subsidiary of Philco Corporation, requested that an investigation be made of the impedance characteristics of various types and configurations of semi-conductor diodes at a frequency of approximately 2200 mc, a cavity power of 3 watts, and under varying bias voltages. The company had constructed a reactance modulated F.M. transmitter using semi conductor diodes for modulation, but was unsure of its maximum modulation capabilities and the losses expected because of resistive losses within the diodes. Another problem confronting the company was initial drift correction within the transmitter. It was hoped that this investigation would clarify the potential of various types and combinations of diodes in overcoming this drift problem.

This report will be presented as a resume of the activities preceeding, during, and subsequent to the actual testing of diodes so that the reader may examine the methods used and enlarge upon various aspects of them at a later date, if he so desires.

The writers wish to express their appreciation for the complete cooperation given by Western Development Laboratories in general and especially to Mr. R. F. Pasos and Mr. G. O. Heninger of the Data Transmission Department.

2. Basic Problem Analysis

A basic description of the transmitter and the form of insertion of the diodes into the cathode cavity was given by Western Development Laboratories personnel. A drawing of the unit is included as Figure 1a. The primary operating characteristics of the unit are as follows:

1) Frequency approximately 2200 mc
2) RF power in the cathode cavity approximately 3 watts
3) Power presently dissipated by the modulating diodes approximately .7 watts
4) Room temperature and standard pressure
5) Diodes currently used are all pigtail, point contact types, in various parallel combinations.

The transmitter is in operation and is being modulated by the diodes, but initial drift correction is being accomplished by using a ferrite phase shifter. It is desired to utilize the diodes for both modulation and drift correction and also to reduce the power dissipated by the diodes. It is not known, at the present time, whether the modulation is being accomplished only by reactance changes, by resistance changes, or by a comination of these.

From an examination of current literature concerning semi-conductor diodes, the following bias voltage-capacitance relations and bias voltage-current relations were obtained, and are shown in Figure 2. It can be seen that a small RF voltage centered at some point on the capacitance curve will give capacitance changes as the RF swings from plus to minus. If this is then coupled into the cathode cavity of Figure 1a, it will create the effect of changing the cavity dimensions thus changing the frequency.

It was desired to keep the testing procedures used closely associated with the actual conditions under which the diodes would be used, i.e., frequency, power, etec. Diode testing has been done at RF frequencies by various individuals and companies, however it is not known if parallel combinations or pigtail type diodes have been tested, or if diodes have been tested under these power conditions.

The problem of a testing configuration was discussed with personnel at Western Development Laboratories, Varian Associates in Palo Alto, and Hewlett Packard Company in Palo Alto. The type of configuration used before in diode testing placed the diode to be tested, (normally a cartridge type), as an integral part of the center conductor in the coaxial cavity. (See Figure 3.) In order to maintain the same characteristic impedance within the coaxial line, the inside diameter of the outer conductor would have to be changed as the center diameter was changed, (to include combinations of diodes). Because of this, and the problem of construction of the apparatus, it was decided to look for a new approach. Western Development Laboratories suggested the possibility of using a coaxial cavity and inserting the diodes into the side of the cavity so that they would be coupled into the field. This idea was discussed with Varian Associates and Hewlett Packard and it was decided that this method would be satisfactory and would also conform more closely with the actual transmitter configuration used by Western Development Laboratories. Cavities were available at Western Development Laboratories which had resonant frequencies in the range desired. It was decided to use the probe configuration already in use by Western Development Laboratories, for holding the diodes in various parallel combinations. The proposed probe and testing combinations, is included as Figures 1b and Figure 4

respectively.

The proposed testing procedure was to be:

1) Set up system as indicated in Figure 4.
   a) Double stub tuner included to match impedance to the testing cavity
2) Take VSWR of system with slotted line shorted, to establish a minimum position
3) Take VSWR with cavity only-no diode probe- to establish the cavity reflection conditions
4) Take VSWR with cavity and correctly tuned probe i.e., minimum VSWR but consistant with about $\frac{1}{2}$ watt power dissipation
5) Take VSWR for various bias voltages, (reverse and forward), and also for various combinations of diodes. The criterion for bias to be established by the current limitations of the diodes.

The cavity to be used was a 50 ohm brass type with the probe insertion point located at a voltage maximum position. Power was to be coupled in at the current maximum position with an inductive loop. (See Figure 5.)

The air and guide wavelength were considered to be the same because of the cavities' air dielectric. (Subsequent investigation proved this true within the accuracy of our measurements.) The wavelength corresponding to a frequency of 2182.5 mc is 13.7457 cm.

3. Diode Testing

The test set up indicated in Figure 4 was put into operation and the test procedures followed. The following pieces of equipment were used:

1) Western Development Laboratories 2182.5 mc 10 watt oscillator for driver
2) Hewlett Packard 1900 to 4000 mc 767 D dual directional coupler
3) Mod. 160-20 20 watt 50 ohm flat Sierra load
4) Hewlett Packard Mod. 200 6D modulation oscillator
5) Hewlett Packard Mod. 415 B VSWR meter
6) Hewlett Packard Mod. 60 slotted line
7) Norda Corp. Mod. 229 900-18,000 mc slotted line probe
8) 2182.5 mc brass cavity constructed by Western Development Laboratories.

From the knowledge that the barrier capacitance of the type of diodes used should be approximately .5 to 5 micro micro farads each, and that parallel combinations of diodes should increase the capacitance, it was assumed that a fairly large phase shift would occur under varying bias conditions. The equipment was assembled and basic procedures were followed in establishing a shorting position, cavity reflection effects etc. The diode probe, which contained 9 1N198 type diodes in parallel, was then inserted, and the minimum location was noted. A very small phase shift occurred however, and various bias voltages on the diodes had little effect on the phase shift. The probe had originally been set up in the transmitter itself to give optimum transmitter operating characteristics and the same set up was used in the testing cavity. The following constants and variables were maintained throughout the examination:

1) Shorting stub length constant

2) Distance of bottom plate from center conductor constant

3) Output, (driver), frequency constant

4) Bias variable

5) Number of diodes variable

6) Types of diodes variable.

Subsequent investigation indicated that the effects created by bias changes on the diode probe, when interrelated with the fields in the cavity, were not sufficient to change the properties of the cavity enough to be measurable with the equipment available. More sensitive equipment was not readily obtainable and therefore this method of testing was discontinued.

It was found that the Microwave Group in the Servo Department of Western Development Laboratories had constructed a brass, air dielectric, 50 ohm, coaxial line with a slotted line section and matching 50 ohm load as an integral part of the line. Input to the brass line was coupled from a standard coaxial cable fitting, and screws were located at the beginning of the line to give optimum matching,(minimum connection reflections), into the brass line. It was decided that another section of brass line could be constructed and a sleeve constructed in the center of it in which to insert the diode probe. This would mean that we would be working into the matched load and thus any impedance changes created by the probe and diodes would be indicated as changes in VSWR and minimum locations, as measured by the slotted line and detection sections of the brass coaxial line. The diagram and general dimensions of the overall testing medium are indicated in Figure 6. The line and other components were set up and are indicated in block diagram form in

Figure 7.

The sections of the line and the other components were tested with no probe inserted in order to determine the overall line characteristics. By proper adjustment of the wedge shaped, carboned paper which was inserted into the end of the last section to act as a load, a VSWR of 1.01 was obtained. A brass washer with wire mesh braid around the edge was used as a shorting device and it was inserted, (without the flat load attached), until it was located under the diode probe sleeve. The VSWR and minimum were measured. The VSWR was approximately 70 which indicated a good short. By location of two consecutive minimums and a notation of the frequency input at the same time it was found that the coaxial line wave length, corresponded, within the limits of our measurements, to the wave length in free space, i.e., 13.75 cm. Since it was felt that the minimum position, for a shorted condition, should lie directly under the center of the probe space, it was decided to take an integral number of wave lengths forward of this hole as an established minimum position for the slotted line. Subsequent investigation indicated that our measured minimum, using the shorting washer in the line, was off by .06 inches. It was felt that this factor substantiated our calculations and therefore our permanent minimum location, with the line shorted, was established. The short was then removed, the matched load replaced, and another VSWR taken to insure correct line matching.

It was decided to use a previously constructed 9 diode 1N198 probe for the first run and to set it up exactly as it is used in the actual transmitter configuration, i.e., same distance between bottom plate and center conductor, same shorting stub length, etec. The probe was set up and introduced into the brass section of the line. Input frequency

and power were maintained relatively constant. The frequency was 2182.47 mc and power in the line was 3 watts. Bias voltage was varied from minus 30 volts to approximately plus .3 volts, at which time the forward current reached the maximum allowed for the individual diode as indicated by manufacture specifications. The data obtained will be examined later.

A second run was made, keeping all items the same as run one, with the exception that the probe contained 6 1N198 diodes and 3 1N198 dummy diodes which had been burned out by discharging a capacitor through them. This was done to keep the physical shape the same as in run one. The shorting stub length was also maintained constant and the same range of bias voltages used. The current in the reverse direction, however, increased slightly in the bias range from about minus 12 volts to minus 9 volts and then conformed to normal theory as bias was further decreased,(going toward a plus value). It was decided to check this phenominon by observing the run with a 3 1N198 diode probe. Results from this run will also be examined later.

The third run was made using the same procedures as previously outlined, however, 3-1N198 diodes were used and no dummy diodes were inserted because it was felt that the results would not be significantly different from those with the dummy diodes. This theory will be substantiated later. The same current increase with negative bias was observed for this run, however, in this case current runaway occurred and the plate voltage of the master oscillator was cut off to keep from burning out the diodes. The run was repeated and again, at about minus 16 volts the current started increasing and then appeared to run away. Subsequent investigation indicated that the current run-away could be controlled by either decreasing the power in the line or by changing the

length of the probe shorting stub. The results for various power settings versus current and bias are indicated in Figure 8 for both the 6 1N198 and 3 1N198 probes.

This phenomenon was discussed with personnel at Western Development Laboratories and three possible reasons for it were given. It was thought that it might be caused by:

1) Hole storage in the diodes
2) The circuit going from parallel to series resonance and the subsequent increase in RF swing causing Zenner breakdown to occur
3) Thermal heating

No conclusion was reached as to the definite cause of this current runaway and it is felt that further investigation in this area is warrented.

This information indicated that it was not feasible to use the same shorting stub length for different configurations of diodes if the same power were maintained. It was therefore decided to revise the testing procedure. The new testing procedure to be used is as follows:

1) Establish shorting position
2) Work into matched load
3) Maintain frequency constant
4) Maintain power input constant
5) Maintain probe bottom plate- center conductor distance constant
6) Adjust shorting stub length to obtain minimum VSWR at minus 30 volts bias
7) Vary bias from minus 30 volts to plus .2 to .4 volts, dependent on indicated diode current
8) Take VSWR, minimum position, diode current, power in, and

power reflected as data.

Using the foregoing criteria, the tests on the three probes were rerun. Information was tabulated and the results will be plotted and examined in the last section of this report.

A test was also run on the VSWR and minimum location effect created as the shorting stub length was varied from a full out to a full in position. The results of this run are plotted on a Smith chart. This is included as Figure 9. It is noted that the plot corresponds closely to a circular or elliptical path, but that it is not centered around the central axis of the chart. It is felt that this may be a constant error in the information taken, however, these results were not plotted until the investigation was completed and therefore the data using this information may be incorrect by a constant amount. Sufficient time was not available to correct the basic data by this constant but it is felt that a phase shift on the Smith chart which would move the observed data into the corresponding place for a "centered" Smith chart position, would correct the results observed for the diodes. The actual positions of the shorting stubs for the three diode probe runs made are indicated in Figure 9.

4. Information Evaluation

As it was stated in the introduction, it was hoped to be able to evaluate the impedance characteristics of various types and combinations of semi-conductor diodes at microwave frequencies. Subsequent analysis of this investigation has indicated that with the testing configuration used it will not be possible to state explicitly what the impedance of the diodes is, however, the data should indicate the changes created by the diodes. Since the other impedance factors remain constant during each run, the changes created should be indicative of the actual impedances created by the various combinations of diodes. This will be altered, however, by some constant amount.

It was not possible to use readily obtainable Smith charts for the impedance calculations because of the very small VSWR values obtained i.e., from 1.2 to 1.02, therefore all values of impedance, (normalized), were calculated from the formula:

$$Z_n = \frac{2\,(VSWR) - j\,(VSWR^2 - 1)\,\mathrm{Sin}\ 2\theta}{(VSWR^2 + 1) + (VSWR^2 - 1)\,\mathrm{Cos}\ 2\theta}$$

where $\theta \cong \pm 360^\circ \lambda_s$ and λ_s is the wave length shift from the shorted position.

From a consideration of the test set up it can be seen that the normalized impedance taken was actually made up of a parallel combination of the line impedance and the probe impedance. (See Figure 10.) From this it can be seen that factors other than those created by the diodes are included. Individual impedances can also be calculated for probes without diodes, (but with all other physical settings the same), to establish the impedance contribution of the shorting stub at the corresponding diode probe positions. It was not known if this information could be correctly eleminated from the diode probe impedance and therefore it was felt that

the investigation results would be more correct if the impedance created by the shorting stub length were left in as a part of the probe impedance.

From a consideration of diode probe and load impedance an A.C. equivalent circuit was developed and is presented as Figure 11. It is not known, because of the unavailability of literature concerning diodes at microwave frequencies, if this is the exact equivalent circuit, but it is felt that the effective impedance of the bias connector may be a series arrangement, as indicated, and that it is in parallel with the actual impedance of the diodes. It can be seen from the complexity of the circuit that the actual measurement of impedance of the diodes would be a difficult task, but it is still felt that the investigation herein completed is indicative of the true diode characteristics and their effects in creating changes within the brass coaxial line.

A plot of the impedance effects created by the diodes is included as Figure 12. It can be seen that the curves for the 9, 6, and 3, diode probes have similar shapes, however, the 3 diode probe exhibits the most marked deviation from the more general pattern. From an examination of Figure 12, the following may be observed:

1) As the number of diodes in parallel decreases, the total normalized resistance increases, (for the minus 30 volt bias position). This conforms with accepted theory.
2) The major overall change in impedance is more resistive than reactive for all three probes.
3) The resistive change is greater for the 3 diode probe than for the other combinations.
4) The reactance change is most pronounced for all three probes from minus 30 volts to about minus 8 volts and is is resistive from minus 8 volts to positive voltages.

5) The reactance at minus 30 volts starts out quite inductive and as bias is changed it becomes less inductive, as would be expected.

6) The peaks which occur for each probe at about minus 1.5 volts bias are unexplained but may be due to some resonance effect at this bias voltage.

The results listed above would tend to indicate that the basic transmitter may be modulated not by reactance changes as was hoped, but rather by resistive changes within the diodes. It is felt that further investigation with other types of diodes might give a type whose changes would be more reactive and therefore more suited to the purposes intended.

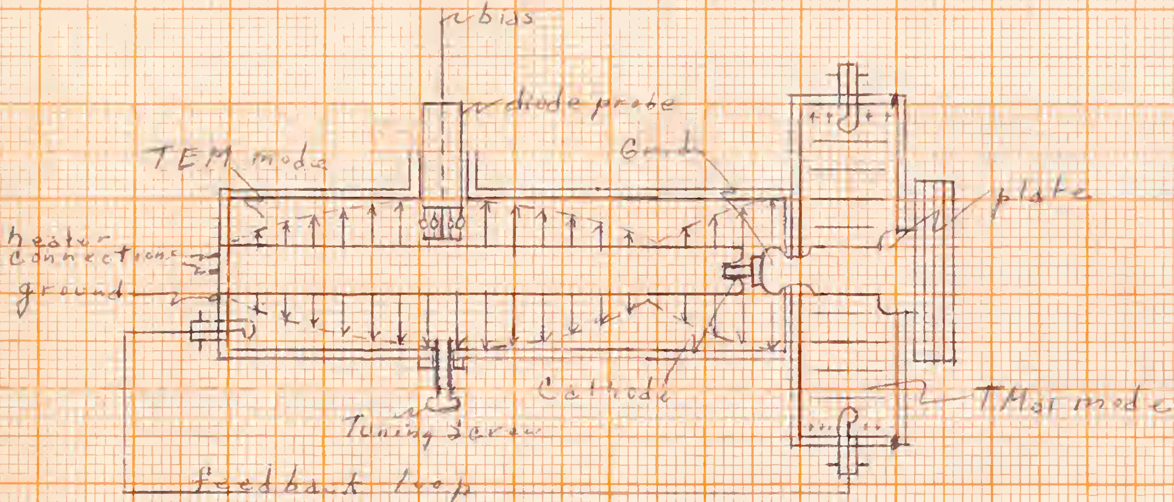
Hindsight now indicates that much better methods, or improvements on this method, could be used in determining the impedance created by diodes. More specifically, it would seem that the following items would improve the reliability:

1) Elimination of the shorting stub by making the diodes enter flush with the inside of the outer conductor.

2) Elimination of the flat plate at the bottom of the diode probe.

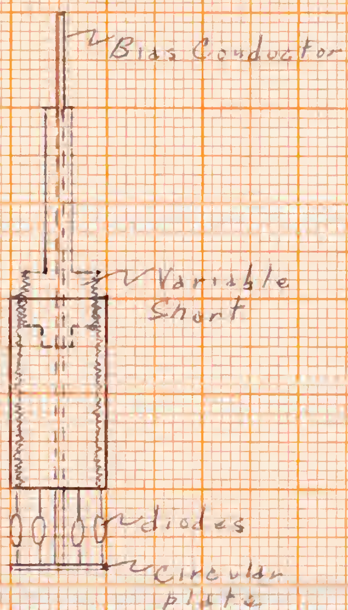
3) Working into a short instead of a matched load, thus being able to use Smith charts.

Although it is realized that this investigation may not add specifically to the present knowledge concerning semi-conductor diodes when exposed to microwave frequencies and reatively high power fields, it is hoped that the information may stimulate further interest in basic investigation of this type, possibly using the methods and suggestions contained herein.



Transmitter Oscillator and Modulator

Figure 1a



Probe Construction

Figure 1b

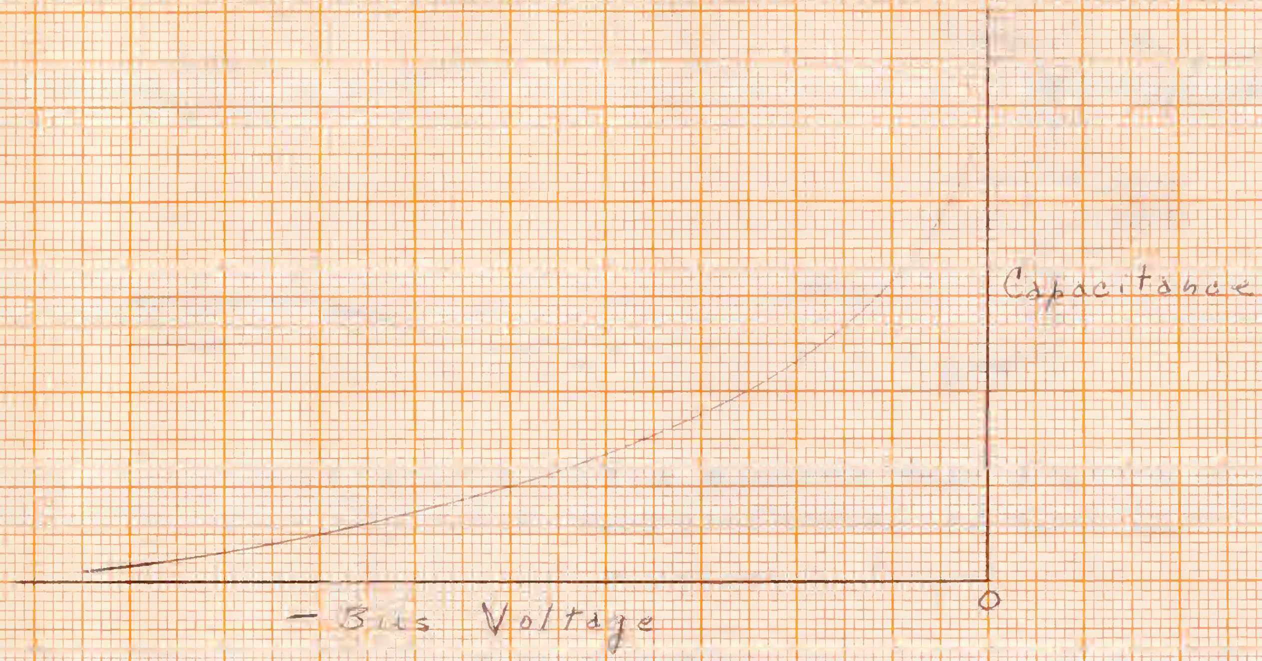


Figure 2

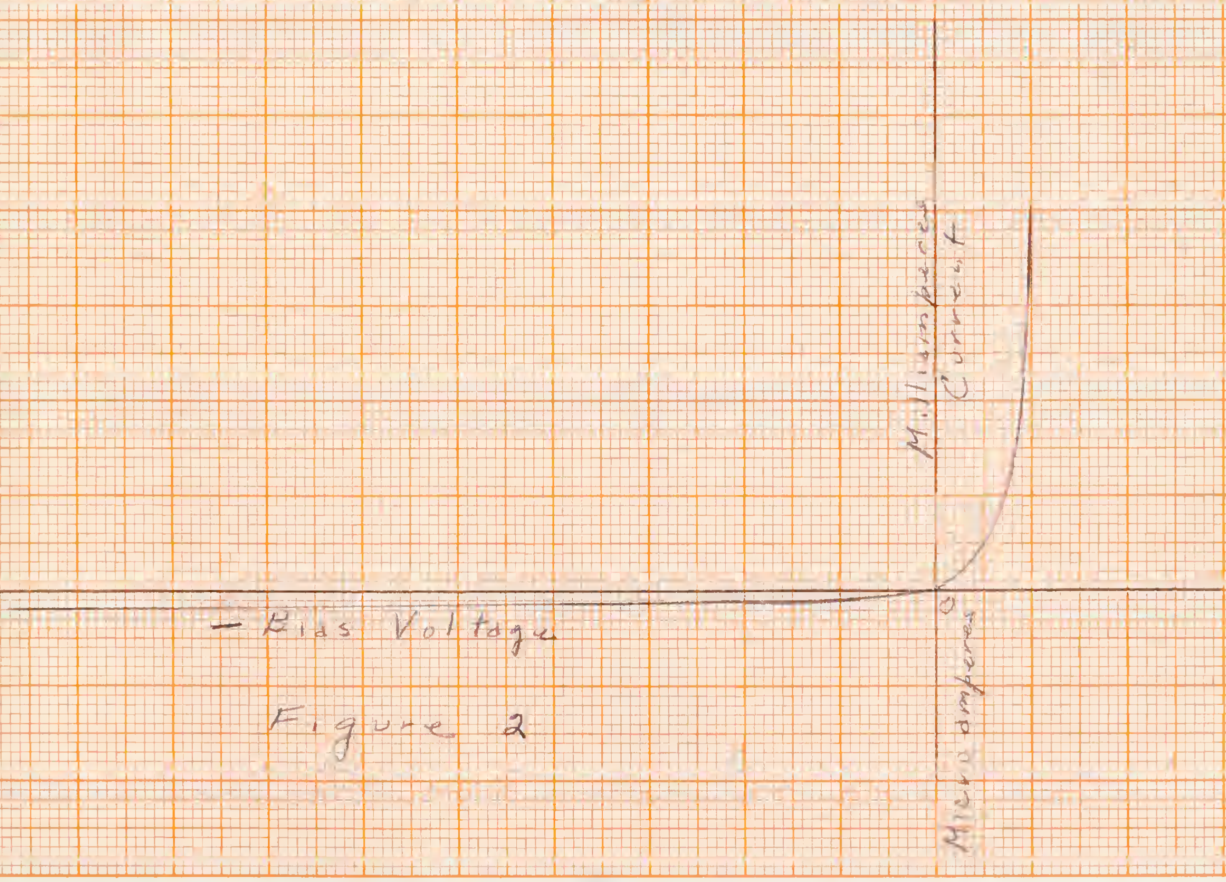
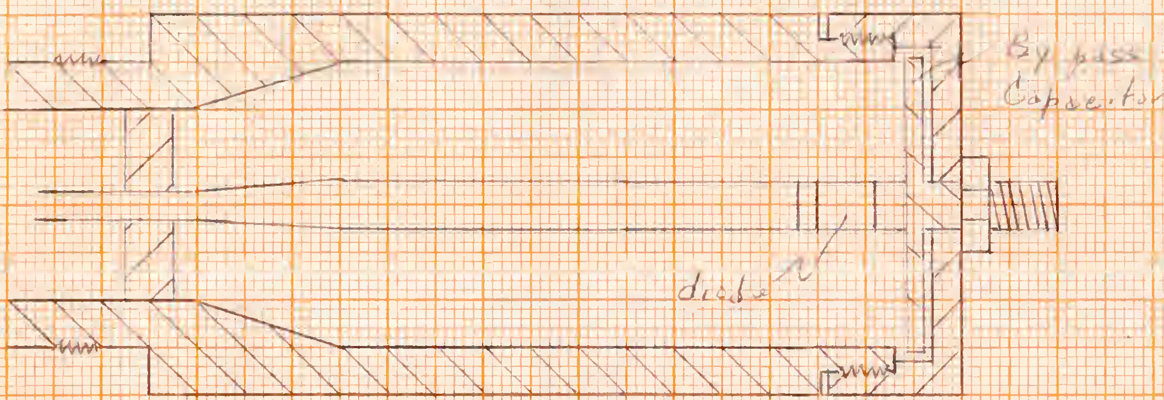
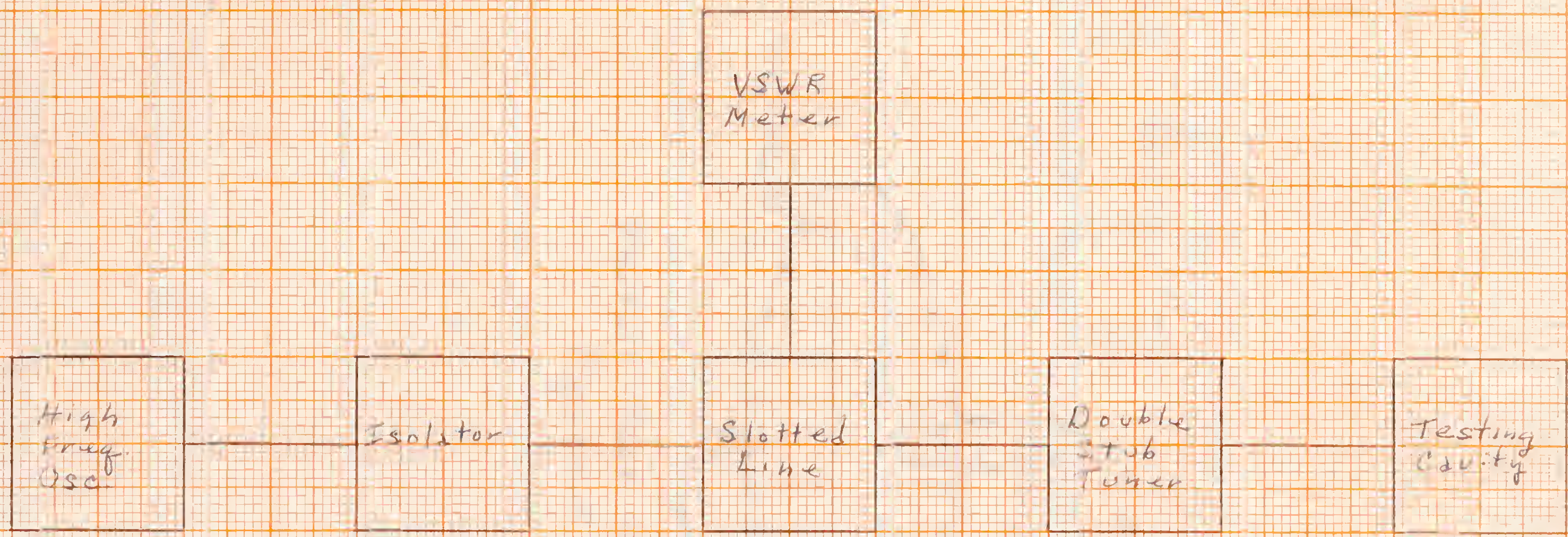


Figure 2



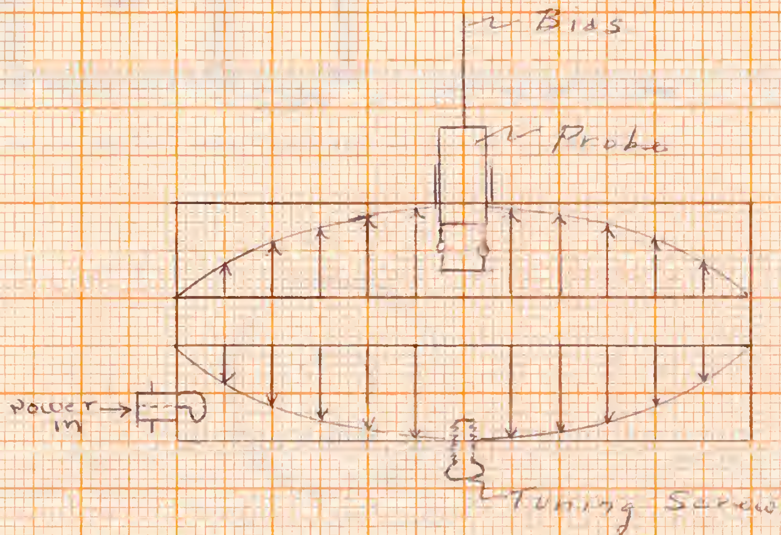
Cross section of a possible test fixture for impedance measurements of cartridge type diodes at microwave frequencies

Figure 3



Original Test Set-up

Figure 4



Initial Test Cavity

Figure 5

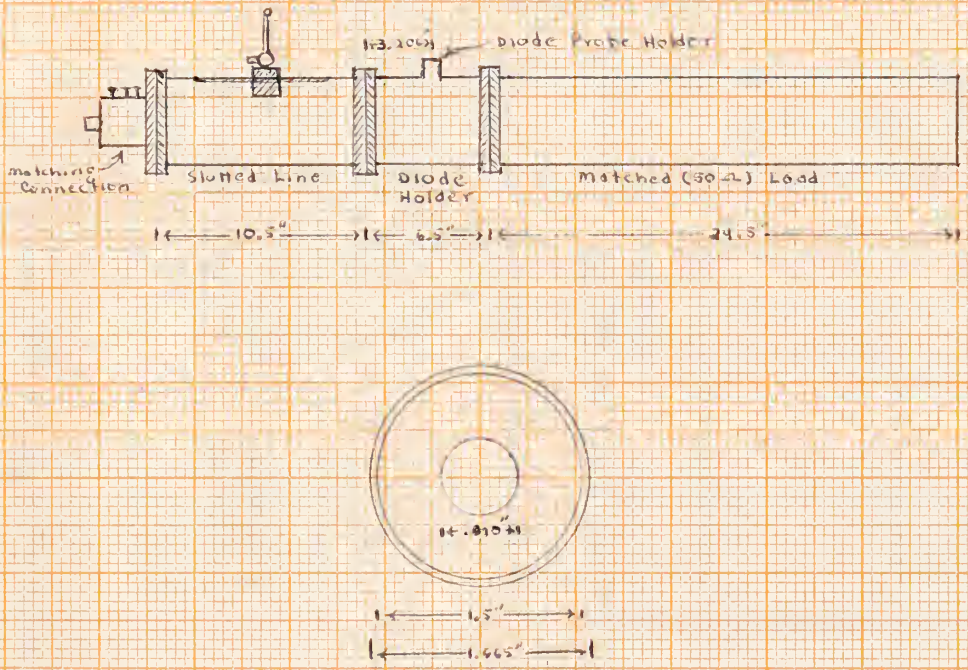


Figure 6

Final Testing and Measuring Section

Final Testing Arrangement

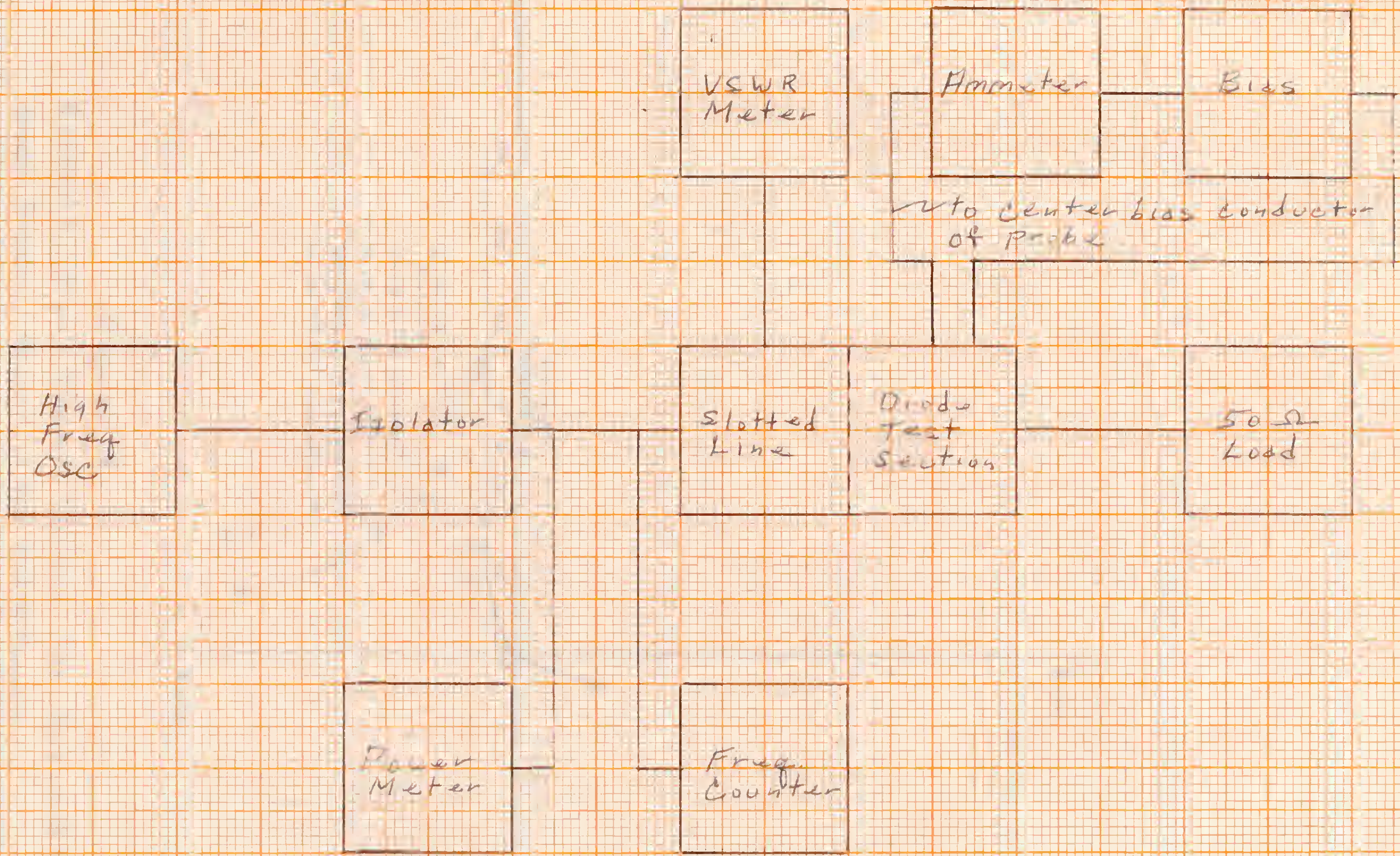


Figure 7

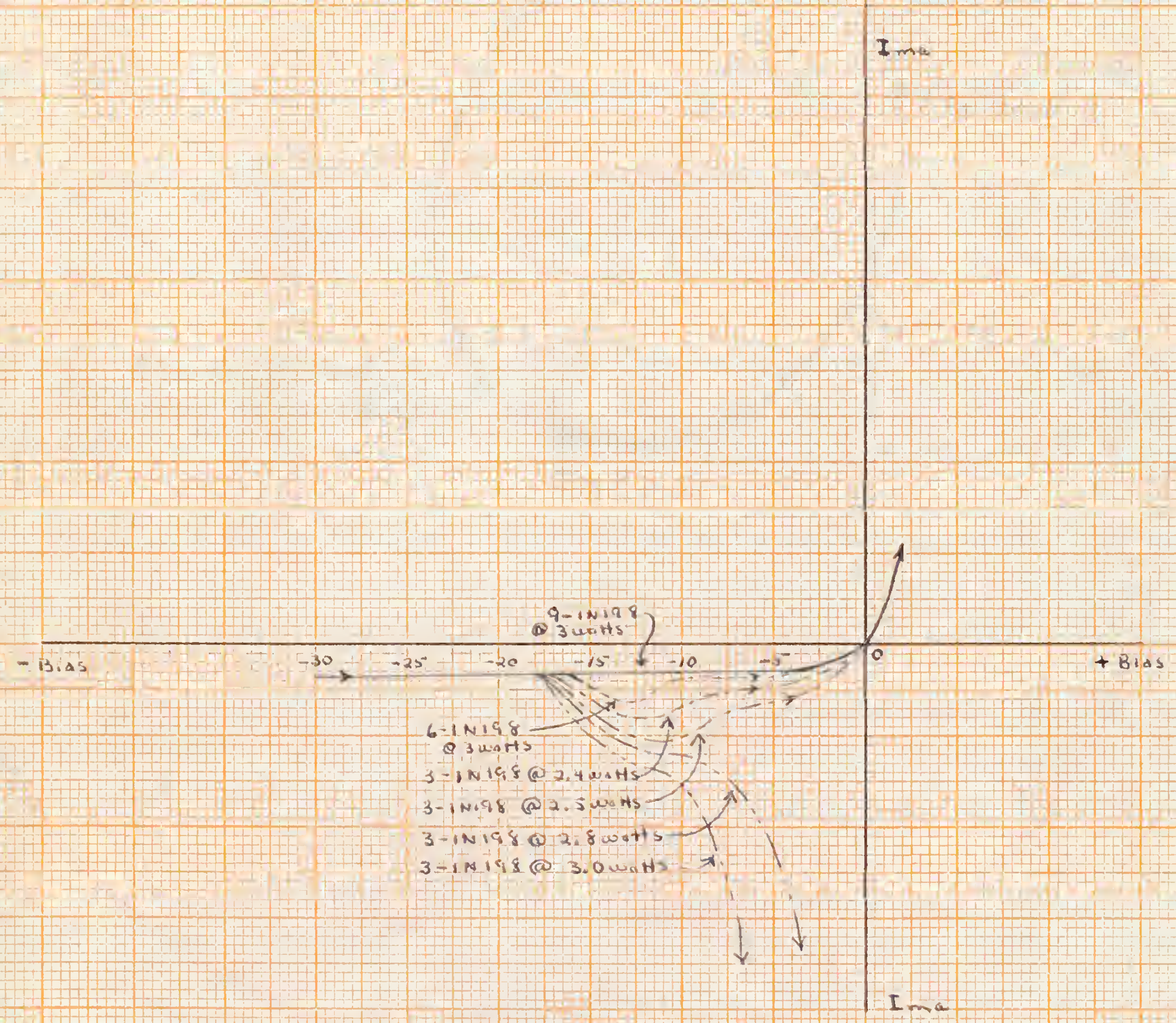


Figure 8

Current - Bias - Power Curves for 3, 6, and 9 Diode Probes. Power is for Field Power

Measured Impedance
of Probe (no diodes attached)
as Shorting Stub Length is Varied

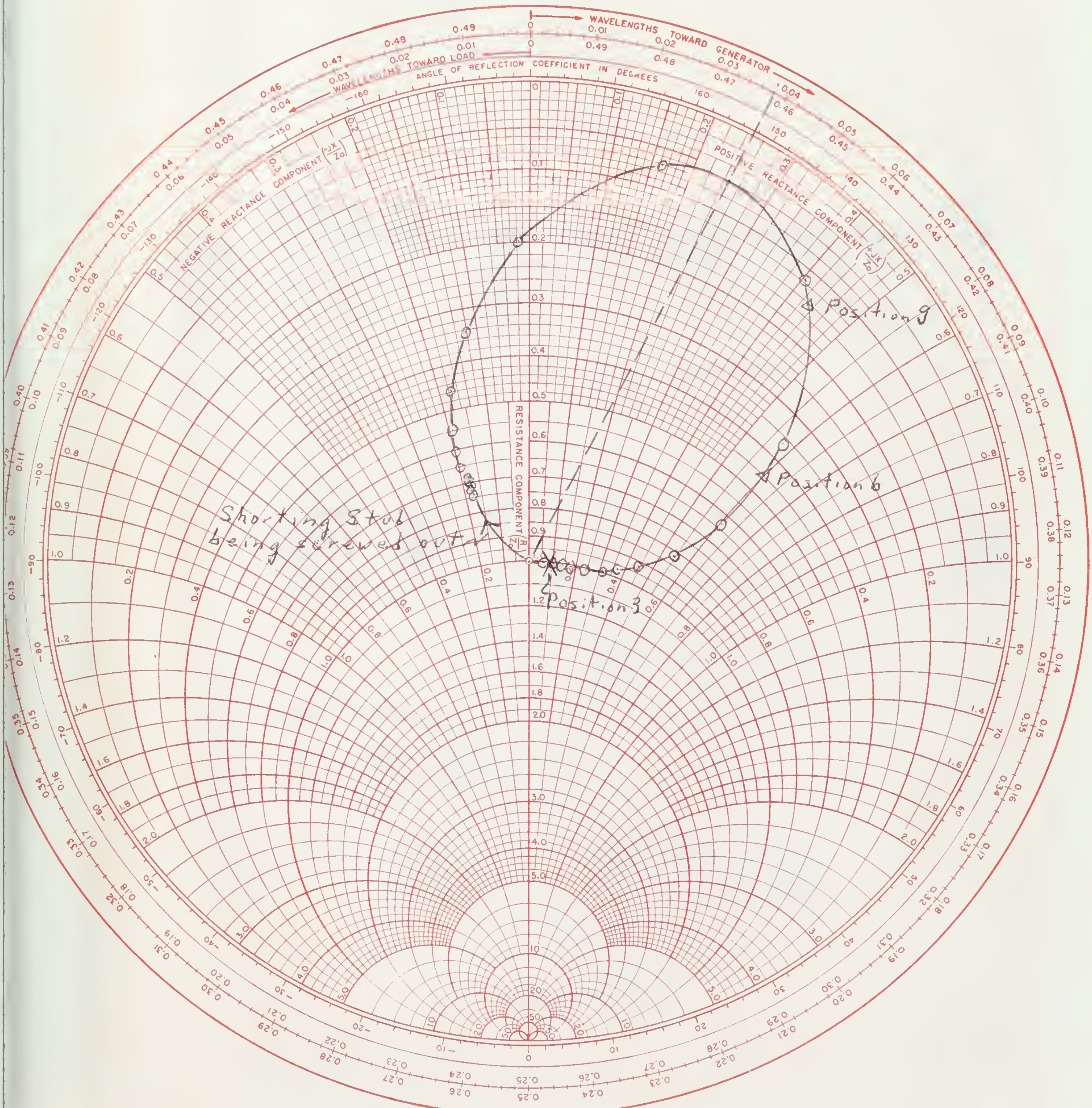
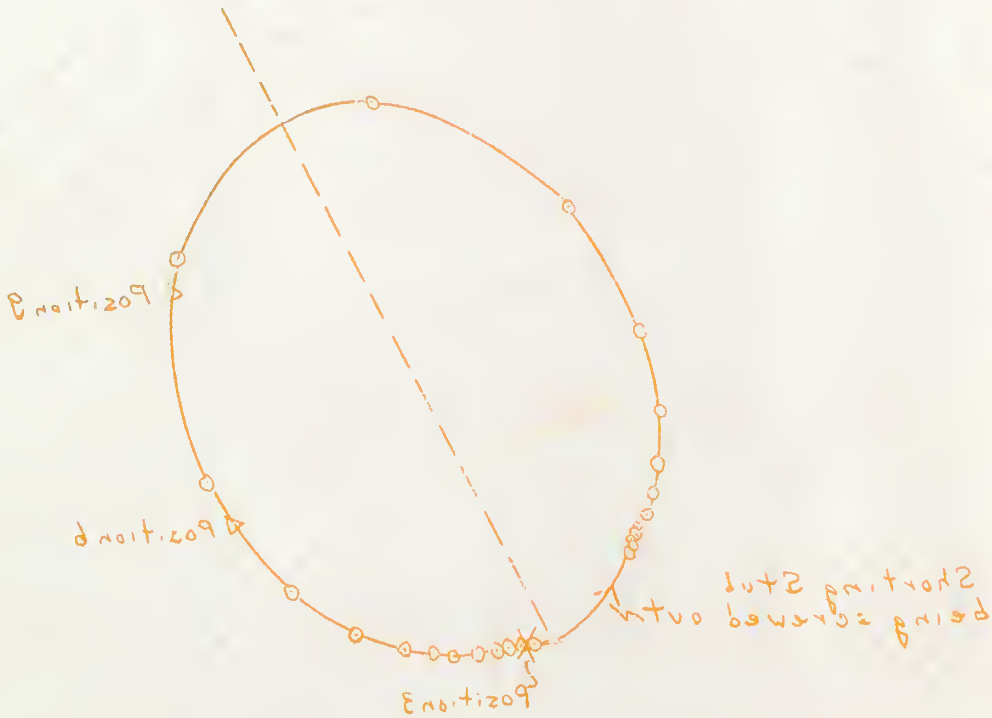


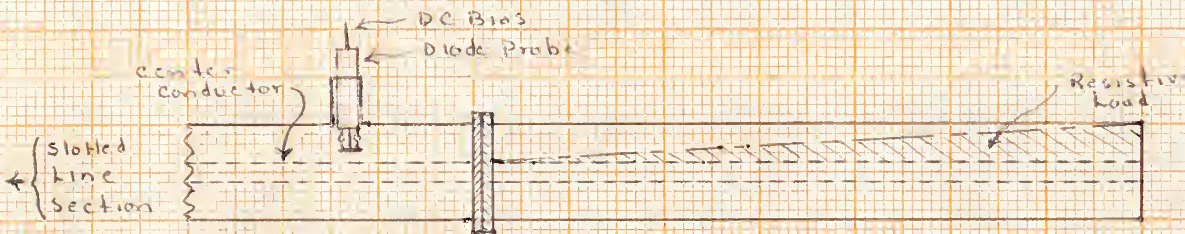
Figure 9

Measured Impedance

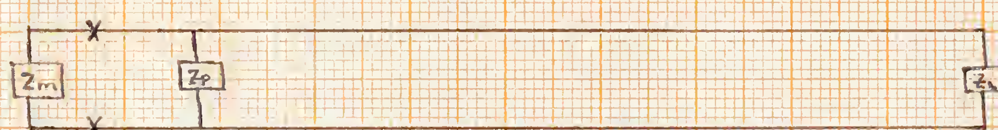
of Probe (no diodes attached)

as Shorting Stub Length is Varied





Basic Configuration



Basic Equivalent Impedances

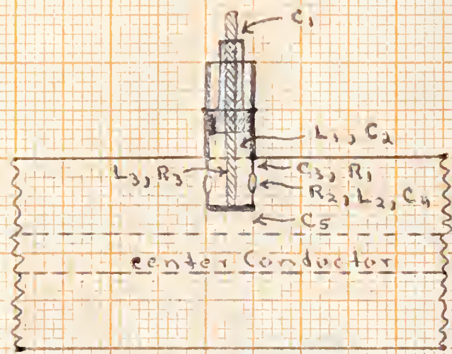
Z_m = Z measured

Z_p = Z probe

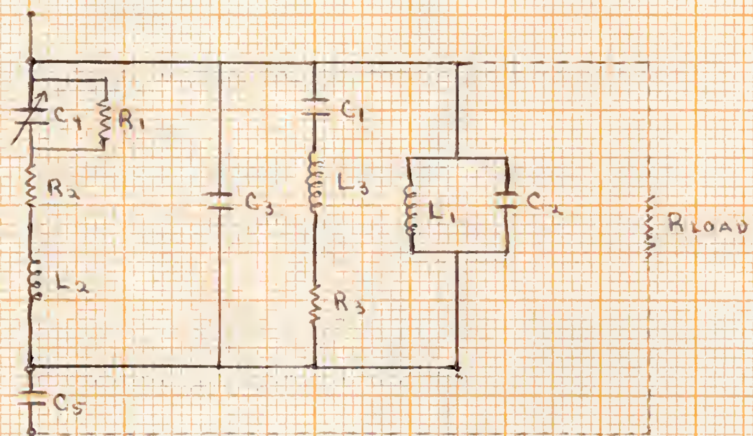
Z_L = Z Load

$$Z_m = \frac{Z_L Z_p}{Z_L + Z_p} \qquad \text{or} \qquad Z_p = \frac{Z_L Z_m}{Z_L - Z_m}$$

Figure 10



Diode Probe and Major Impedance Factors



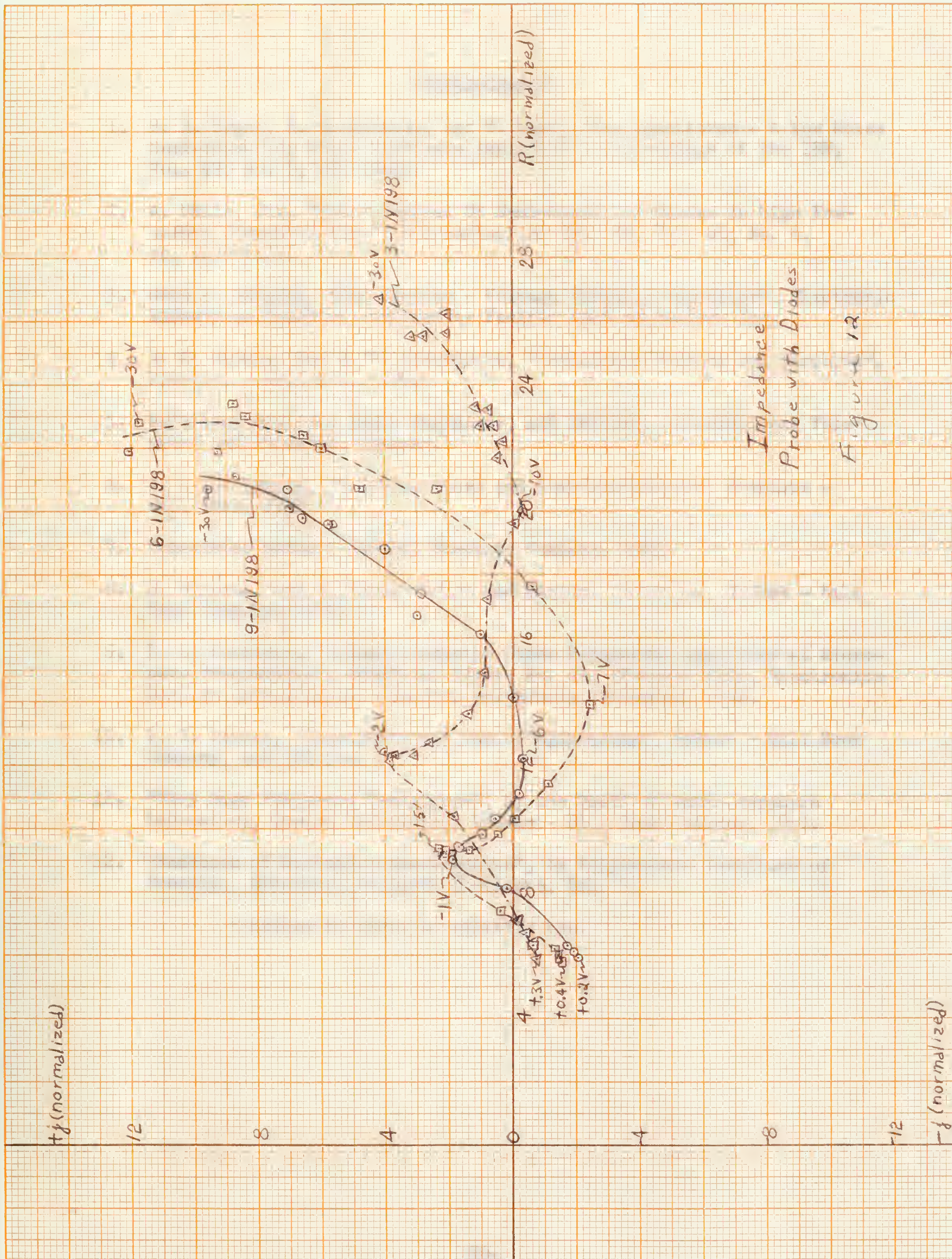
Equivalent A.C. Circuit of Diode Probe

R_1 = Diode Package
R_2 = Diode Series
R_3 = Center Bias Pipe

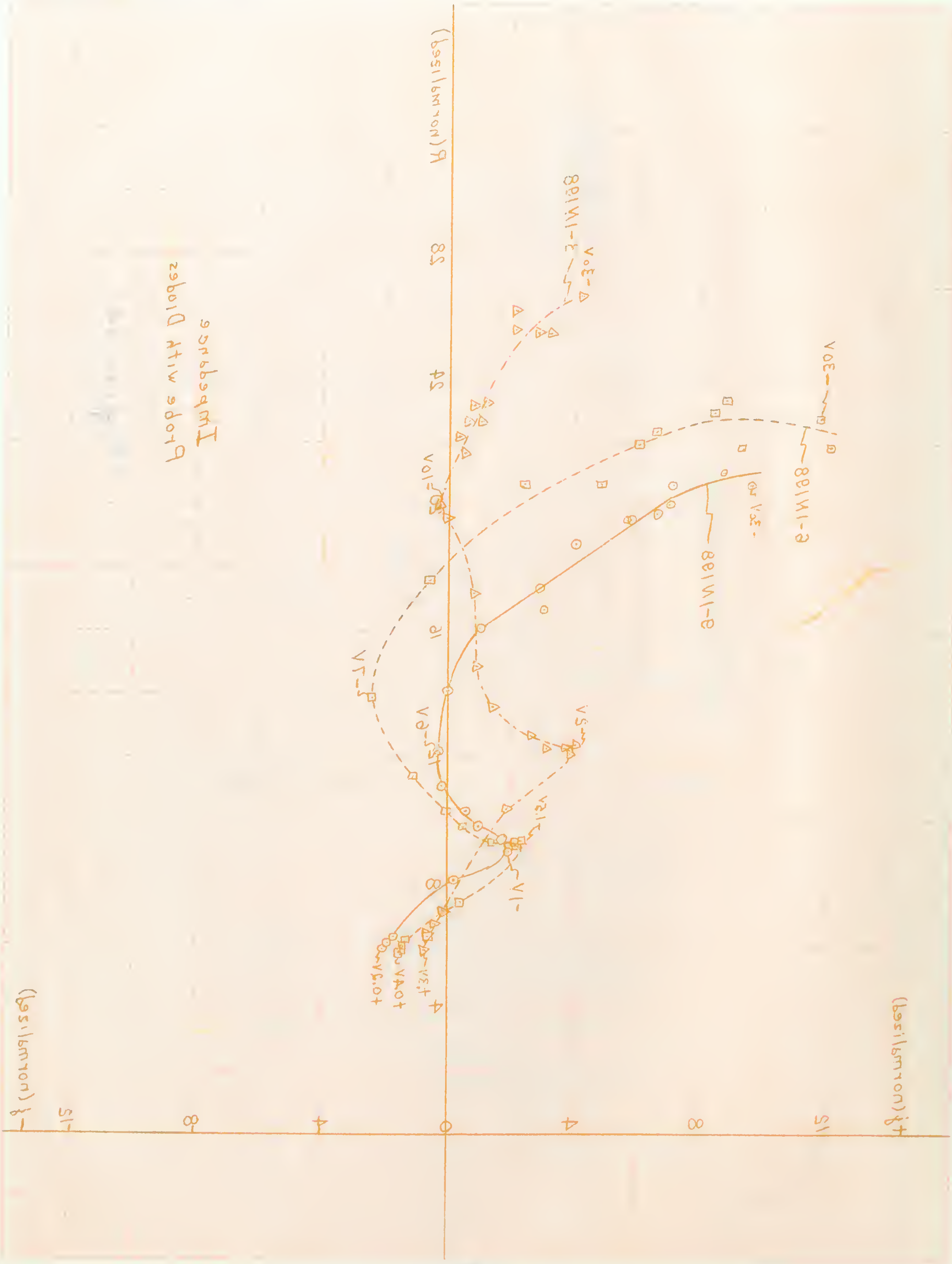
C_1 = Pipe to outer Conductor
C_2 = Shorting Stub Cavity
C_3 = Diode Package
C_4 = Diode Variable (barrier)
C_5 = Bottom Plate to Center Conductor

L_1 = Shorting Stub Cavity
L_2 = Diode Package
L_3 = Bias Pipe

Figure 11



Impedance
Probe with Diodes
Figure 12
R (normalized)
+j (normalized)
-j (normalized)
3-1N198
6-1N198
9-1N198
-30V
-10V
-7V
-6V
-2V
-1.5V
-1V
+.3V
+0.4V
+0.2V
4
8
12
16
20
24
28


Impedance
Probe with Diodes

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* Listed in order of relative use.